BBC RD 1988/7

Research Department Report

POLARISATION CONVERTERS FOR A DBS FLAT-PLATE ANTENNA

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Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

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Summary

The introduction of a direct broadcast by satellite television service requires suitable receiving antennas to be available. A polarisation converter and an array of linearly-polarised elements have been found to be the most suitable way of receiving the circularly-polarised radiation that would be transmitted by a DBS satellite. In this Report the performance of various types of polarisation converters is considered. It was found that a meander-line polariser gave a cross-polar discrimination of better than 25 dB and an insertion loss of less than 1 dB over the required band. It should be possible to build the polariser using relatively low-cost materials thus making it suitable for use in this application.

Issued under the Authority of

M.E.B. Moffat

**Research Department, Engineering Division,
BRITISH BROADCASTING CORPORATION**

(RA-246)

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1. INTRODUCTION

The introduction of a direct broadcast by satellite (DBS) television service requires suitable receiving antennas to be available. It was originally assumed at the World Administrative Radio Conference of 1977 (WARC-77)[1] that a parabolic dish antenna would be used. However, this approach may be environmentally undesirable and poses significant mechanical constraints on the dish mounting assembly.

An alternative solution to the parabolic dish antenna is a flat-plate antenna. Such an antenna consists of a large number of antenna elements the outputs of which are combined together by transmission lines. The phased-array principle is used to receive signals from the desired direction – which may not be, and indeed usually is not, orthogonal to the plane of the antenna. This gives a flat-plate antenna a number of potential advantages over a parabolic dish – for example it could be mounted flat and hence unobtrusively on an outside wall or roof. However, a domestic flat-plate antenna should be low-cost so that it could compete favourably with a parabolic dish. As a result low-cost materials and construction techniques should be used.

The overall design of a flat-plate antenna which can be mounted flat on the most favourable wall of a building is considered in Ref. 2. The antenna design considers three, somewhat interactive, problems;

(a) receiving circularly-polarised signals,

(b) achieving sufficient antenna gain and directivity,

and (c) collecting the signals from each antenna element so as to receive signals from the desired direction.

Reception of circularly-polarised signals can be achieved either by using circularly-polarised elements or linearly-polarised elements with a polarisation converter. The polarisation converter, or polariser, would be mounted in front of the array and convert the incident circularly-polarised signal to a linearly-polarised one. Currently, the most suitable element for the DBS application has been found[2] to be a linearly-polarised one, and hence this has generated the requirement to design a low-cost polarising screen for the front of the antenna.

In this Report we will consider the performance of various types of polariser. The advantages and disadvantages of each will be discussed and the most suitable for this application chosen.

The requirements for an ideal polariser for use with the antenna proposed in Ref. 2 can be summarised as follows. To allow reception of the DBS transmissions, the polariser should operate over the frequency range 11.7 GHz to 12.1 GHz; it should have as low a transmission loss as possible and a cross-polar discrimination of better than 20 dB. In the final array the main beam will be steered in one plane over a range of angles 16° to 52° on only one side of broadside. The polariser must therefore exhibit the required characteristics in these directions. In addition, the interactions between the array and the polariser should be minimised. For the final array to be suitable for the domestic market, the materials and construction techniques used should be low-cost.

2. TYPES OF POLARISER

Three types of polariser were considered in the course of our investigations. These consisted of the parallel-plate polariser, the wire-grid polariser and the meander-line polariser. The basic operation of these polarisers is however the same, and is often best understood in terms of conversion of linearly-polarised radiation to circularly-polarised radiation, although because of reciprocity the opposite conversion works the same way. In all cases the linearly-polarised radiation is incident at 45° to the structure of the polariser and may be considered as two equal amplitude, spatially orthogonal components, Fig. 1. One of these components is phase-shifted with respect to the other in passing through the structure and the resulting radiation is then circularly polarised.

2.1 Parallel-plate polariser

A parallel-plate polariser consists of a set of parallel metal plates. The plates are inclined at an angle of 45° to the electric field vector of the linearly-polarised wave, Fig. 2. The design of parallel-plate polarisers is discussed by Lait[3], and the theory below is based on his work. More detailed analysis has shown[4] that 45° may not be the optimum angle for the polariser plates as it fails to allow for the different amplitude distributions of the two components of the polariser field.

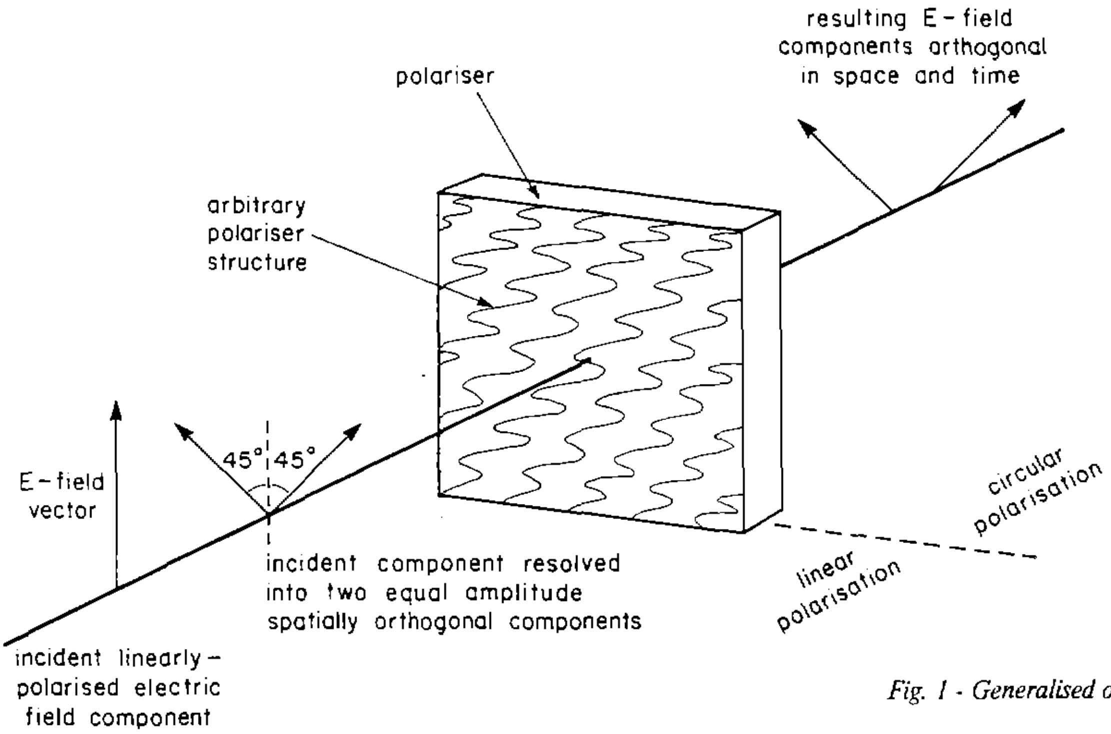

Fig. 1 - Generalised operation of a polariser.

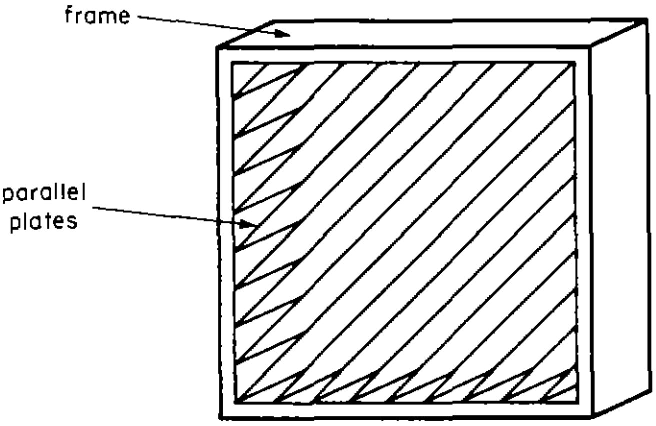

Fig. 2 - Parallel-plate polariser.

The electric-field vector is considered to have two components with vectors parallel and perpendicular to the metal plates. The plates are considered to be infinitely long, perfectly conducting, infinitely thin and parallel. The perpendicular component of the electric field is considered to be unaffected by the polariser and propagates as a TEM wave through the structure with a phase velocity equal to the speed of light. The parallel component of the electric field is constrained to form a TE_{10} parallel-plate mode to pass through the structure.

To produce perfect circular polarisation from an incident linearly-polarised wave, the parallel component of the electric field must be passed with no reflection and its phase must be advanced by 90° relative to the perpendicular component of the electric field. The condition for minimum reflection is satisfied by making the depth of the polariser equal to an integer number of half wavelengths in the parallel-plate mode. To achieve maximum bandwidth the lowest available integer is selected. The condition for the correct relative phase shift is then satisfied by making the depth of the polariser equal to three-quarters of the free-space wavelength. Taking these conditions together the polariser depth and plate spacing can be found.

For the TE_{10} mode the width of the plates can be found to be 0.75 wavelengths and the separation 0.67 wavelengths.

So far the polariser has been considered as a waveguide section, separating two regions of free space. The analysis can be extended to cover the junction between these regions. An equivalent circuit which allows for the junction effects can be taken from Ref. 5. In this analysis reference planes are assumed which allow for the effect at the ends of the parallel plates. When this effect is included in the analysis, the optimum width and spacing of the plates can be calculated to be 0.607 wavelengths and 0.655 wavelengths respectively.

The analysis could be extended to allow for illumination of the polariser by an antenna with a slewed beam. The impedance match and relative phase shift between the modes through the polariser change with angle of incidence. In addition, it has been shown[6] that grating lobes are caused when parallel-plate polarisers are illuminated by radiation with a phase taper.

2.2 Wire-grid polariser

A wire-grid polariser, Fig. 3, consists of a number of planar layers of wires with a suitable spacing between the layers and the wires in any one layer. The wires are inclined at an angle of 45° to the electric field vector of the incident linearly-polarised radiation.

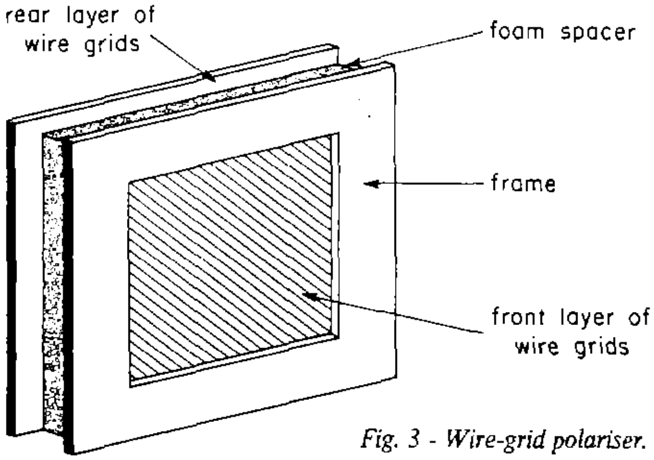

Fig. 3 - Wire-grid polariser.

As before, the electric field vector can be resolved into two components, one parallel and the other perpendicular to the wires. Assuming the wires to be infinitely thin then their effect on the perpendicular component of the electric field is negligible. The effect on the parallel component of the electric field is equivalent to an inductive shunt susceptance. The value of the expected susceptance can be obtained from Ref. 7. From this analysis some indication of the effect of illumination of the polariser by an antenna with a slewed beam can be seen; in that, as with the parallel-plate polariser, the value of the susceptance and the spacing of the components due to each layer will change with the angle of incidence.

Lait[3] used the equivalent circuit given in Ref. 7 to design polarisers consisting of 2, 3 and 4 grids of wires.

2.3 Meander-line polariser

The meander-line polariser, Fig. 4, consists of several printed-circuit sheets each covered with an array of conductive meander lines. The sheets are spaced about one-quarter wavelength apart. The basic approach is to make an array of structures which appear to be predominantly inductive to one polarisation and predominantly capacitive to the orthogonal polarisation.

The meander-line polariser was first devised at the Stanford Research Institute. References relating to the original work are not available in the open literature and design equations have not been published. However, experimental dimensions and results for a four sheet meander-line polariser have been published[8] for a polariser designed to operate over 8 GHz - 12 GHz. These results showed good performance and so it was decided to experimentally investigate this form of polariser further.

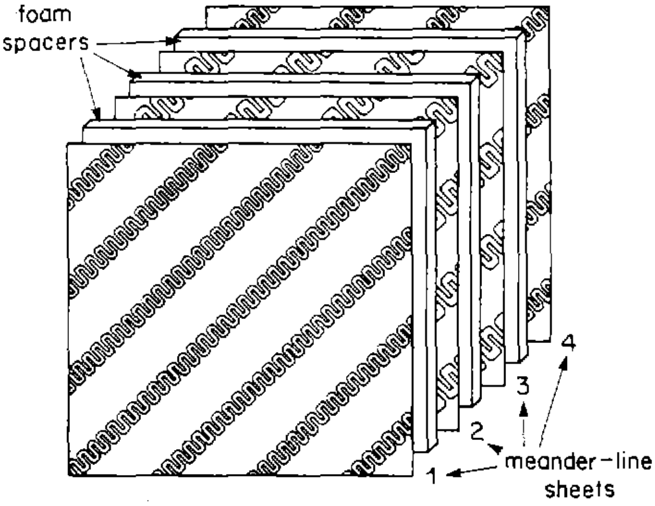

Fig. 4 - Meander-line polariser.

3. MATERIALS AND CONSTRUCTION TECHNIQUES

To produce a domestic flat-plate antenna it is essential that the cost of the antenna should be kept low. In practice this means that its cost should be similar to that of a parabolic dish antenna complete with feed and mounting arrangement. To achieve this the cost of the materials and construction techniques used in a flat-plate antenna must be kept low. As a result it is necessary to keep the cost of the polariser to a minimum.

It is also necessary that the antenna should be mechanically rugged and protected from the effects of wind, rain and snow. As the polariser is the outside layer of the flat-plate antenna, it is envisaged that it could also provide a protective layer (radome) over the antenna.

Therefore the materials and construction techniques used in the polariser were selected carefully. For the wire-grid and meander-line polarisers a printed-circuit etching technique could be used, with the conductive pattern being etched from a copper layer coated on one side of a thin supporting material. In some of the polarisers a PTFE substrate was used as the supporting material, however PTFE substrates manufactured for microwave applications are not low-cost so in other experiments a polyimide film was used. The sheets were spaced using a microwave foam which is relatively low-cost and low-loss at the required frequencies. The parallel-plate polariser required a different technique as the plates do not lie in the plane of the array. Initially, the parallel-plate polariser consisted of a number of metal plates air-spaced and held at the correct spacing in a wooden frame. Later versions consisted of thin aluminum foil sheets spaced by sheets of low-loss microwave foam. This technique could be used in mass production; however, a suitable protective radome structure would then have to be added. All the structures were glued together using thin layers of a commercially available spray adhesive. The properties of the adhesive at microwave frequencies were poor; however, only very thin layers were used, which were thought to have little effect on the performance of the polarisers.

4. EXPERIMENTAL RESULTS

A number of polarisers have been built and measured. The measuring arrangements consist of a linearly-polarised transmitting antenna which is mechanically rotated and a linearly-polarised receiving antenna of known radiation pattern and good cross-polar discrimination in front of which is mounted the polariser under test. The transmitting antenna is rotated and the variation in the received signal level is recorded. This variation is the axial ratio of the polariser. The cross-polar discrimination of the polariser to circularly-polarised radiation can be found from the axial ratio. The general case of elliptical polarisation and the interpretation of measurements made using a rotating linearly-polarised source are considered in more detail in the Appendix.

4.1 Parallel-plate polariser

A large parallel-plate polariser consisting of a number of metal plates, air spaced and mounted in a wooden frame was measured. The spacing between the polariser and the receiving antenna was found to be important. Fig. 5 shows the variation in the broadside axial ratio with array-to-polariser spacing. It can be seen that a standing wave is set up between the array and the polariser and that every half wavelength the axial ratio passes through a minimum. This variation was explored at three frequencies spaced across the lower half of the DBS band and was found to be similar at all frequencies. The variation of axial ratio with frequency was also investigated and found to be sufficient to cover the required bandwidth (see Fig. 6).

A polariser consisting of a sandwich of aluminum foil and microwave foam was also constructed and measured. The same variation of axial ratio with array-to-polariser spacing was observed, Fig. 7, and the radiation pattern of the array/polariser

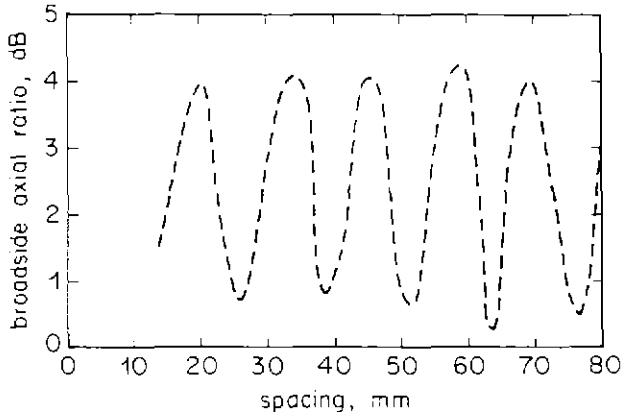

Fig. 5 - The variation in axial ratio with array-polariser spacing for an air-spaced parallel-plate polariser at 11.9 GHz.

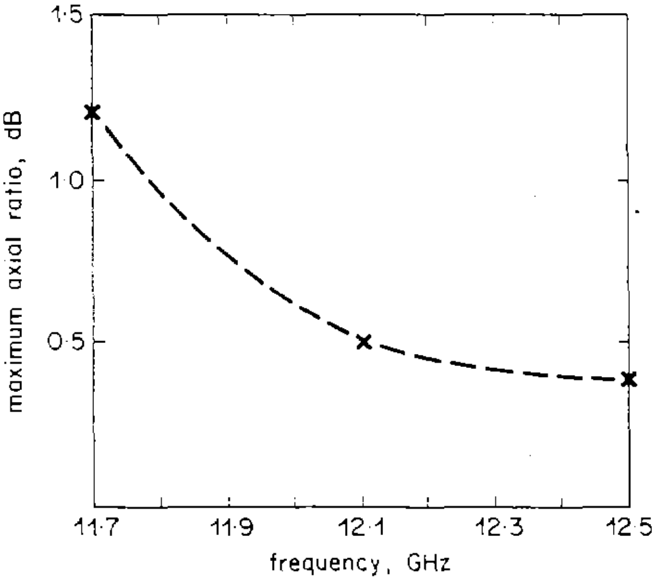

Fig. 6 - The variation in broadside axial ratio with frequency for an air-spaced parallel-plate polariser.

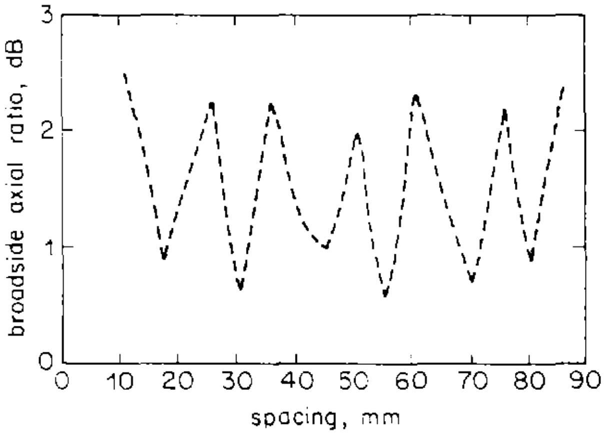

Fig. 7 - The variation in axial ratio with array-polariser spacing at 11.9 GHz for normally incident radiation on a foam/foil polariser.

combination was measured, Fig. 8. These results showed that a polariser could successfully be constructed using a foam/foil sandwich technique and broadside axial ratios of between 0.5 dB and 2.5 dB could be achieved over the required band.

The polariser was also mounted in front of a receiving antenna with a slewed main beam. The variation of axial ratio with angle of incidence of the radiation on the polariser was measured, Fig. 9. These results show that a good axial ratio can be achieved with a slewed antenna main beam. It was expected from other reported work[6,9] that grating lobes would be observed in the plane of the slew, however no evidence of this was observed. In all cases the polariser insertion loss was found to be less than 1 dB.

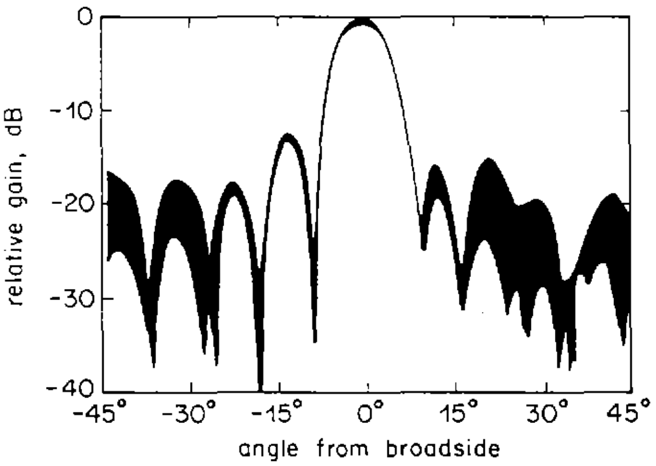

Fig. 8 - The radiation pattern of a broadside array and foam/foil parallel-plate polariser at 11.9 GHz.

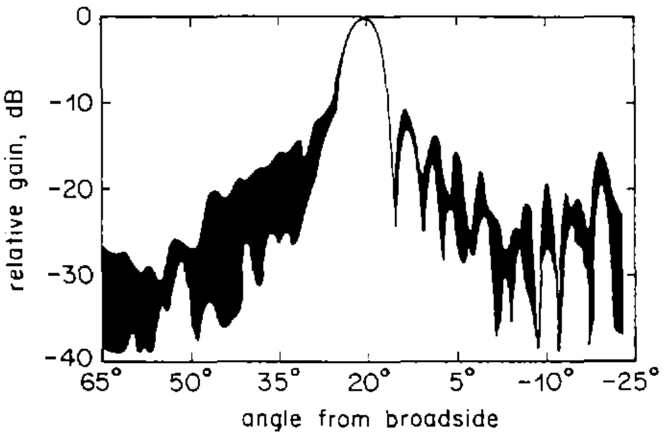

Fig. 9 - The radiation pattern of a slewed main-beam array and air-spaced parallel-plate polariser at 11.9 GHz.

4.2 Wire-grid polariser

A wire-grid polariser, based on a design by Lait[3], was constructed and measured. It consisted of wires etched from a copper sheet, supported on a polyimide substrate with the layers spaced using a microwave foam. A two-layer structure was investigated initally and a third layer was subsequently added to try and improve its performance. The variation of the axial ratio with frequency for the two- and three-grid polarisers is shown in Fig. 10. The three-grid polariser showed a slight increase in usable bandwidth along with an increase in the operating frequency; however the bandwidth was still lower than required. A variation in the axial ratio with array-to-polariser spacing was also observed, this followed the same trend as was observed with the parallel-plate polariser. In both cases the polariser insertion loss was found to be low.

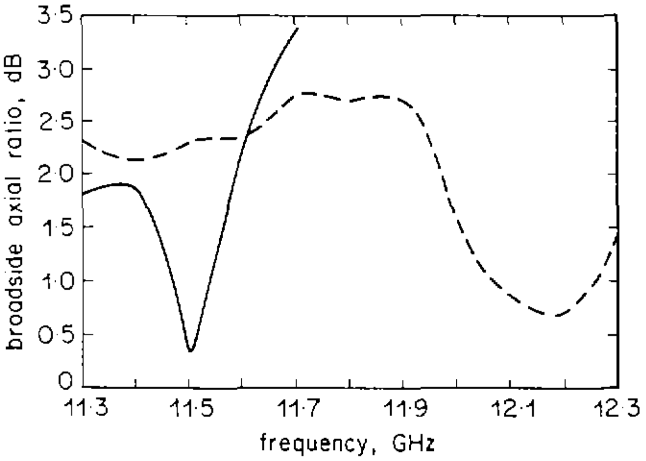

Fig. 10 - The variation in broadside axial ratio with frequency for 2- and 3-layer wire-grid polarisers.

——— 2 grid polariser
— — — 3 grid polariser

4.3 Meander-line polariser

A meander-line polariser comprising four layers of meander lines was constructed. The dimensions used were those given in Ref. 8. Initially the lines were etched from a copper sheet supported on a thin layer of PTFE substrate. The layers were spaced using rigid microwave foam and the assembly was fixed using spray adhesive.

The polariser was measured placed in front of a broadside flat-plate receiving array. The results again show the variation in the axial ratio with array-to-polariser spacing, Fig. 11. The radiation pattern of a polariser and broadside array was measured, see Fig. 12. These results show the very good performance that can be achieved with a meander-line polariser. It was also found, as suggested in the design paper[8], that the polariser operated over a wide bandwidth. The periodic variation in the axial ratio with array-to-polariser spacing was investigated further. This was done by exciting each of the orthogonal polarisations independently and measuring the transmitted signal level. The results, Fig. 13, show that the periodicity is due to a standing wave in the component with its electric-field vector across the meander lines. This is presumably due to a slight mismatch between the polariser and free space for this component.

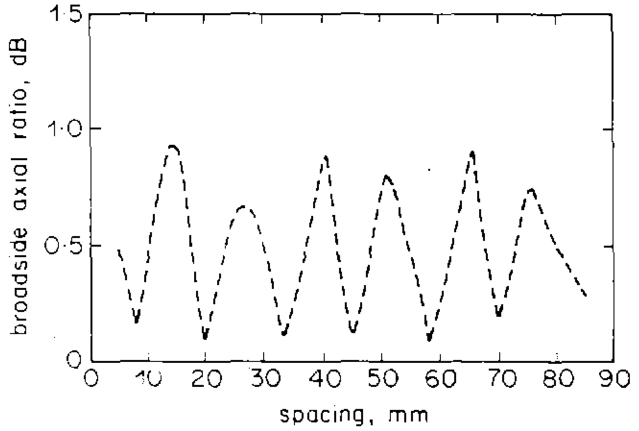

Fig. 11 - The variation in axial ratio with array-polariser spacing at 11.9 GHz for normally incident radiation on a meander-line polariser.

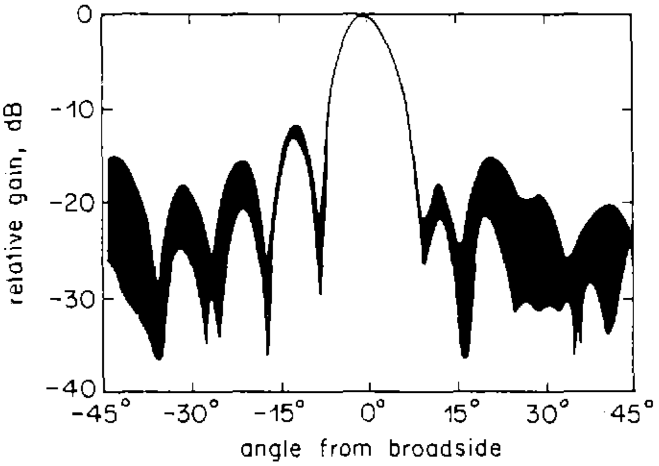

Fig. 12 - The radiation pattern of a broadside array and meander-line polariser at 11.9 GHz.

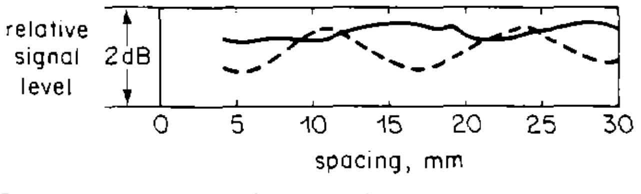

Fig. 13 - Transmitted level of the two electric field components through a meander-line polariser at 11.9 GHz.

—— E-field along the meander lines

- - - E-field across the meander lines

The polariser was also placed in front of a slewed main beam flat-plate antenna. Similar measurements were performed and the results are given in Figs. 14 and 15. Once again it can be seen that a good axial ratio can be obtained over the main beam, although the variations in axial ratio with array-to-polariser spacing have increased. In all these measurements the polariser insertion loss was found to be less than 1 dB.

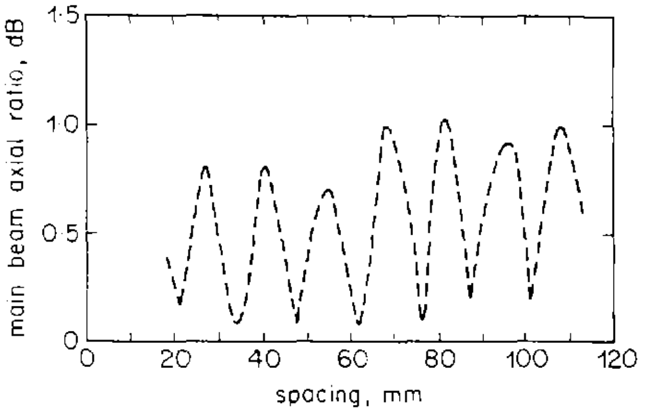

Fig. 14 - The variation in axial ratio with array-polariser spacing for radiation incident at a 20° slew angle on a meander-line polariser at 11.9 GHz.

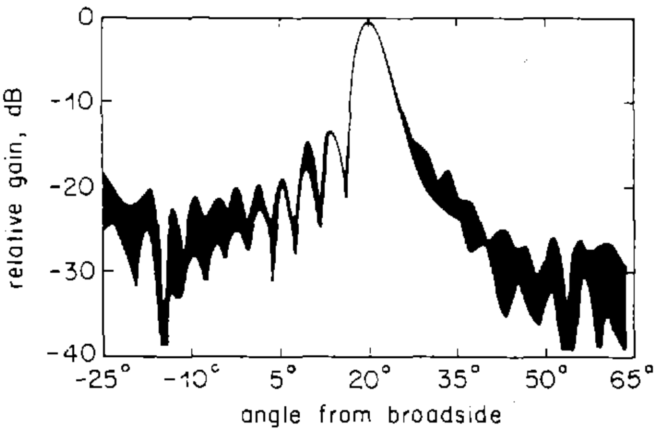

Fig. 15 - The radiation pattern of a slewed main beam array and meander-line polariser at 11.9 GHz.

5. DISCUSSION

Three types of polariser suitable for mounting in front of a flat-plate antenna have been constructed and measured. The axial ratio obtained on the boresight (not necessarily broadside) of the receive antenna placed behind the polariser was the primary measure of its performance.

The wire-grid polariser showed poor performance and a relatively narrow operating bandwidth. A relatively narrow bandwidth was expected from theoretical considerations; however the experimental results showed a bandwidth that was even narrower. These results could perhaps be improved by careful optimisation of the wire diameter and spacing and by the introduction of more layers into the structure, but considerable improvement would be required before the polariser met the required performance. The construction techniques and materials used were similar to the those used in the construction of the antenna and so would easily satisfy the low-cost criteria for the polariser.

The parallel-plate polariser performed well giving a low axial ratio over the DBS band. The measured axial ratio, when suitably spaced from the array, was less than 1 dB over the band. An investigation into the performance of the polariser when used with an array with a slewed main beam was conducted. It was expected that a grating lobe structure would be seen, as has been reported elsewhere; however no such structure was observed. This sort of polariser, made from low-cost materials such as a sandwich of aluminum foil and microwave foam, gave good results similar to those obtained with an air-spaced structure. In spite of this, such a structure might still be relatively expensive as the construction method used for the array could not be extended to the polariser and a protective radome would still have to be added.

The meander-line polariser showed excellent performance over a wide bandwidth. The measured axial ratio was consistently less than 1 dB over a range of array-to-polariser spacings and dropped at some spacings to less than 0.25 dB. The polariser was also found to operate satisfactorily when used with an array with a slewed main beam. This type of polariser uses construction techniques similar to those used in the construction of the array. In the original polariser, PTFE substrate material, which is expensive, was used to support the meander lines. It should be possible to replace this with a polyimide film such as was used in the wire-grid polariser. This would make the polariser cheaper. The only disadvantage to the meander-line polariser is that analysis of the structure is very complicated and the design method is not available in the open literature.

6. CONCLUSIONS AND RECOMMENDATIONS

Three types of polarisation converter, or polariser, have been considered in this Report. In the case of the first two, the parallel-plate and wire-grid polarisers, the design equations have been published elsewhere and it was possible to design a polariser to operate over the required band. However, the design equations for the third type, a meander-line polariser, are not freely avaliable and so an 8 GHz - 12 GHz version designed elsewhere was investigated.

A number of polarisers of all three types have been constructed and measured. The results show that the performance of the meander-line polariser was better than the parallel-plate polariser which was itself considerably better than the performance of the wire-grid polariser. The axial ratio of the meander-line polariser was less than 1 dB (a cross-polar discrimination of better than 25 dB) over the required band and its insertion loss was less than 1 dB. It was also shown that a meander-line polariser performs well when used in conjunction with an array producing a slewed beam in one plane. However further work would be required to obtain a good theoretical understanding of the operation of a meander-line polariser; this theoretical understanding should allow for array/ polariser interactions and operation with an array with a slewed main beam.

The meander-line polariser is recommended for use in a flat-plate antenna for the reception of DBS transmissions. It is relatively easy to construct and could be made using low-cost materials and techniques. Its structure is such that the top layer could be used as a weather-proof radome.

7. ACKNOWLEDGEMENT

The authors would like to acknowledge the work of J.A. Boyer in the measurement of some of the wire-grid polarisers.

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APPENDIX

Interpretation of Measurements made on an Elliptically-Polarised Antenna using a Rotating Linearly-Polarised Source

Elliptical polarisation can be characterised by the ellipse generated by the electrical and magnetic field vectors as they rotate. The rate of rotation is, of course, the angular frequency, ω. Linear and circular polarisation are special cases of elliptical polarisation. Any elliptically-polarised wave can be considered as the sum of two orthogonal waves, either linearly polarised or circularly polarised. An arbitary ellipse is shown in Fig. A.1. This can be resolved into co-polar and cross-polar components of linear-polarised waves:

power in co-polar component $= \alpha^2/2\eta$

power in cross-polar component $= \beta^2/2\eta$

where: α = electric field vector along the major axis

β = electric field vector along the minor axis

η = impedance of free space

The polarisation can also be resolved into components of circularly-polarised waves:

power in co-polar component $= (\alpha+\beta)^2/4\eta$

power in cross-polar component $= (\alpha-\beta)^2/4\eta$

In each case the power in the wave is given by:

power $= (\alpha^2+\beta^2)/2\eta$

In the WARC-77 plan for DBS it has been specified that circular polarisation should be used. Radiation patterns are measured using a rotating linearly-polarised source antenna. The result is a direct measure of the axial ratio of the antenna; however, it is necessary to interpret the axial ratio measurements produced in terms of co-and cross-polar components of circularly-polarised radiation.

If the axial ratio, $A(\text{dB}) = p_1 - p_2$

where: p_1 = maximum power received by a rotating linearly-polarised antenna (dB),

p_2 = minimum power received by a rotating linearly-polarised antenna (dB),

p_1 and p_2 correspond to the major and minor axes of the elliptically-polarised radiation. It can be shown that the power that would have been received had the antenna been illuminated by co-polar circularly-polarised radiation, p_{wanted}, is given by:

$$p_{\text{wanted}}\,(\text{dB}) = p_1 + 20\log[1 + 10^{-A/20}] - 3$$

A similar calculation can be made to find the cross-polar discrimination of the antenna, where the cross-polar discrimination (XPD) is defined as the ratio of the co-polar to cross-polar components. This can be shown to be given by the equation below and is plotted in Fig. A.2.

$$XPD(\text{dB}) = 20\log\{[1 + 10^{-A/20}]/[1 - 10^{-A/20}]\}$$

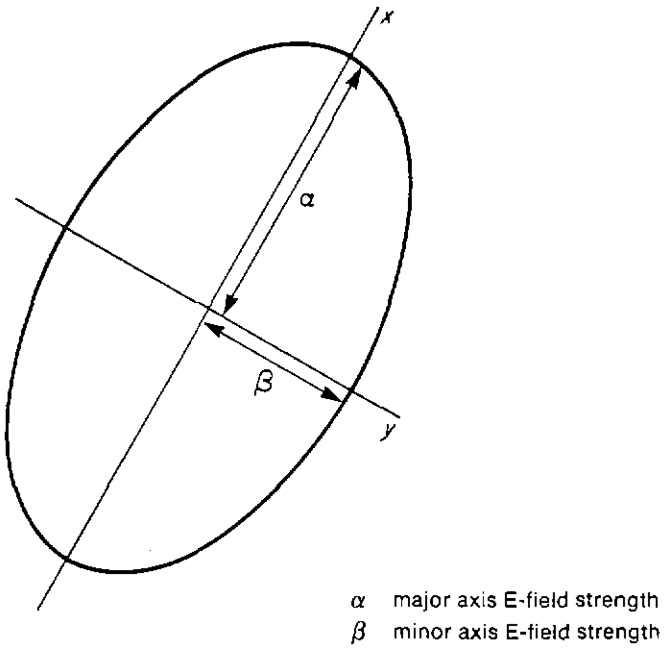

Fig. A.1 - Arbitrary polarisation ellipse.

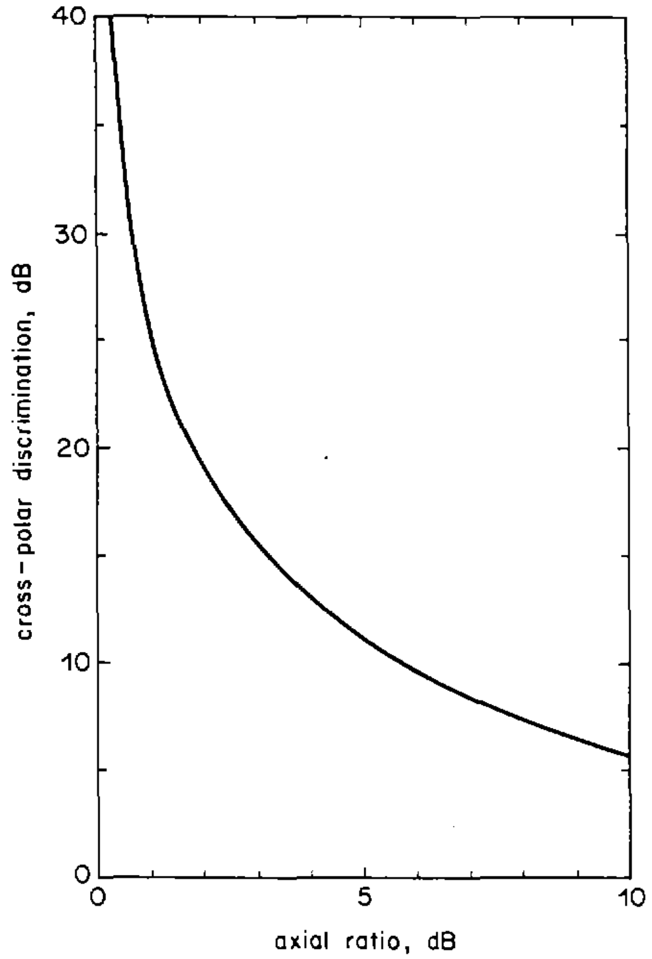

Fig. A.2 - Cross-polar discrimination as a function of axial ratio.

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